THE SIGNAL CHARACTERISTICS ANALYSIS FOR THE USE OF GNSS IN THE CHANG'E 5T1 MISSION[1]

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Abstract: *GNSS has long been expected to be used in satellite autonomous navigation above the GNSS constellations. The performance of a high sensitive GPS/GLONASS receiver mounted on the CE-5T1 Service Module are introduced and the characteristics of the signals received from 2014.10.23 18:56:32.275 to 21:53:35.000 UTC are analyzed in this paper. The presented results validate the EIRP models of GPS satellite antennas by reversing the received signal power and show a proximate 100m positioning error if using both GPS and GLONASS signals. It is found that the CE-5T1 spacecraft flied by GLONASS satellite R06 and deep investigations show that the fly-by leads to a obvious rise in the received signal power and Doppler change rate, as well as a marked reducing in GDOP value.*

Keywords: *CE-5T1, GNSS, EIRP, Fly-by, GDOP*.

1. Introduction

Man-made spacecraft "New Horizons" flied by the Pluto at July of 2015, nine years after launched. The space exploration extends to the deeper and deeper space, and correspondingly the mission period extends longer and longer. How to hold the cost (both manpower and material resources) to an acceptable level is a crucial problem for the researchers, including those of Beijing Aerospace Control Centre (BACC) whose work mainly depends on ground-based measurement and control system. CE-5 lunar explorer is expected to be sent to the moon in 2017, while its advance team, CE-2, CE-3 and CE-5T1 spacecraft, might be still on operation in space. To reduce the on-ground operation, BACC begins to study the feasibility of using Global Navigation Satellite System (GNSS) in Lunar spacecraft orbit determination and autonomous navigation.

It is well known that GNSS is designed for users on or near the Earth. However there has been long speculation in the GNSS user community about the viability of GNSS-based satellite navigation from orbits above the GNSS constellations[1]. There are several successful experiences of GPS application in satellites navigation from low Earth orbit (LEO) to high Earth orbit (HEO) [2]-[8]. Decades of researches show that the primary obstacle for space GNSS users is the sparse and weak nature of GNSS signals[6] because only the signals from 'the other side' of the Earth, usually the side-lobe signals, can be received above the constellations and the signal power is effectively low after the long distance travel.

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To test the feasibility of using GNSS in the autonomous navigation of China's future Lunar explorers, two GNSS receivers were equipped to the CE-5T1 spacecraft. Although the receivers can only process GPS and GLONASS signals and worked in limited time, we still can get an intuitive understanding and bring forth some conclusions from analyzing the collected data.

2. General Description of the CE-5T1 GNSS Payload

The CE-5T1 spacecraft, launched at 23rd October 2014, consists of two modules - a Service Module (SM) and a Return Vehicle (RV). The RV conducted a circumlunar flight with a duration of eight days and landed in Siziwang Banner of China's Inner Mongolia Autonomous Region while the SM is still on operation. Two sets of GNSS receiving equipment were mounted on SM and RV respectively. Thereinto, the RV GNSS receiver came into service only before the separation of RV and SM when the orbit height is lower than that of the GNSS satellite to testify the fast acquisition performance. Thus this paper only concerns the SM GNSS receiver, whose parameters are shown in Tab.1[9].

Table 1. Some primary performance parameters of the GNSS equipment on CE-5T1 SM

Parameters	Design performance
Compatible signal	GPS L1/GLONASS L1
Antenna	2, quadrifilar helix (Earth direction and radial direction)
Parallel processing capability	24 satellites (16 GPS sat. & 8 GLONASS sat.)
Acquisition sensitivity	-175dBW
Tracking sensitivity	-180dBW (including the receiver antenna gain)

It is important to note that there are two quadrifilar helix antennas pointing to the opposite direction to guarantee sufficient received signals no matter when the spacecraft is above or below the GNSS constellations. The gain patterns of these two antennas are the same as shown in Figure 1. The maximum gain is 6dBi and the 3dB beam width of both antennas is about ± 55 degrees. This receiver can only process 24 satellite signals at the same time in consideration of the payload power consumption but has an enhanced acquisition and tracking sensitivity to suit for the weak signal processing in space applications.

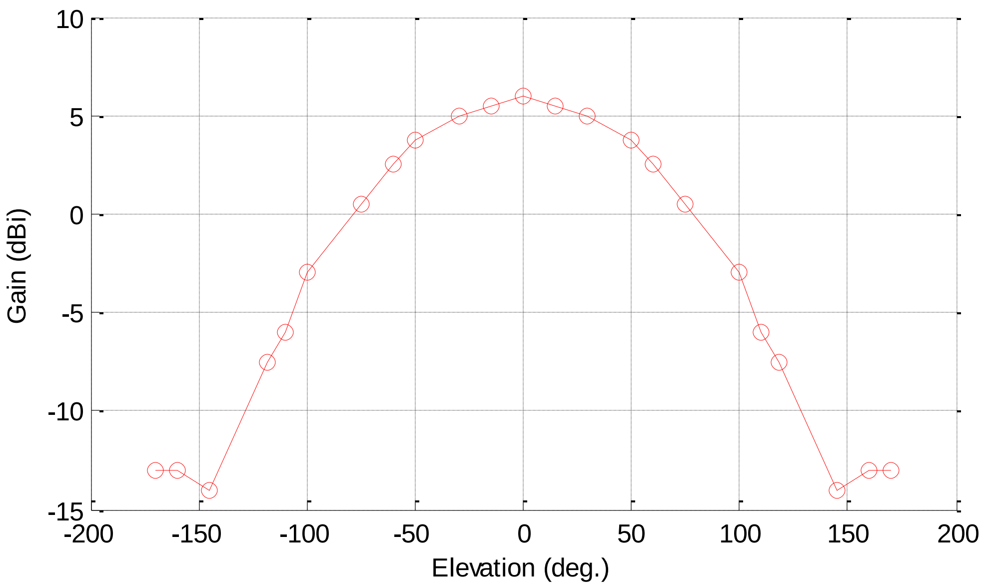


Figure 1. The gain pattern of the GNSS antenna mounted on CE-5T1 SM

The GNSS equipment mounted on SM was powered on three times for about 10 hours totally, and this paper focuses on the data collected from 2014.10.23 18:56:32.275 to 21:53:35.000 UTC (the 413808^{th} to 424431^{st} second of GPS Week 1815) when CE-5T1 spacecraft flied towards the Moon the first time. According to precise ephemeris provided by BACC, the orbit height of the CE-5T1 spacecraft is calculated and shown in Figure 2. It is clear to see that CE-5T1 spacecraft rose from about 17,763 km to 59,374km over this time span and flied across the GNSS constellations from the 415400^{th} to 415700^{th} second of GPS week 1815. The GNSS data was recorded with a sampling interval of 3 seconds including carrier phase, pseudo-range, Doppler and carrier-to-noise ratio (CN0). Some useful conclusions can be drawn from analysis of the received data.

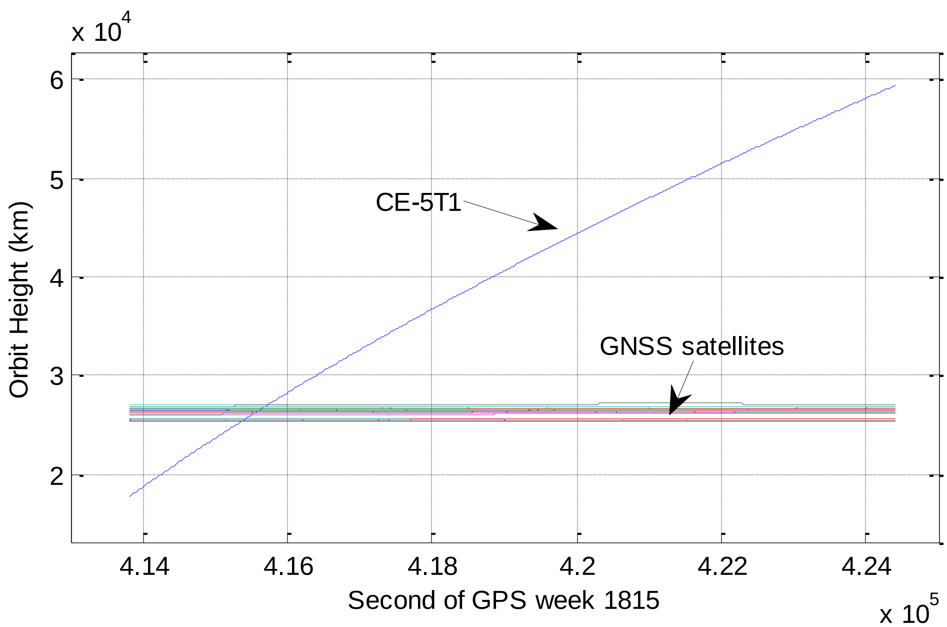


Figure 2. The orbit height of CE-5T1 spacecraft and GPS/GLONASS constellations

3. GNSS Signal Characteristics Analysis

3.1. The Received Signal Power

According to the definition of CN0, the received signal power P_s can be computed using the following equation:

$$P_s = CN0 - 10\log_{10}(KT) \qquad (1)$$

where the Boltzmann constant K= 1.3806505×10^{23}J/K and the system temperature T=298.5K. As shown in Figure 3, all the signal power values fluctuate within (-160dBW, -180dBW) except that of satellite R06. The average level of satellite R06's signal power is obviously higher than that of other satellites and the normal level for ground users (about -160dBW). By investigating the range between satellite R06 and CE-5T1 spacecraft (Figure 4), it is easy to find out that the spacecraft was flying by this GLONASS satellite and the closest distance was only about 2000km. In addition, the received signal power of satellite R06 slides about 30dBW to -175dBW very quickly after reaching its peak because the received signal is from transmitter antenna back lobe when the spacecraft is flying away from satellite R06.

Fly-by leads to a rise not only in the signal power but also in the change rate of Doppler. As illustrated in Figure 4, the maximum change rate of Doppler between R06 and CE-5T1 achieves 96Hz/s which is almost three times the value of other satellites. This high dynamic problem is not difficult to be solved because a raw estimation of the Doppler and its' change rate obtained beforehand using the designed CE-5T1 orbit parameters and GNSS could narrow the search range.

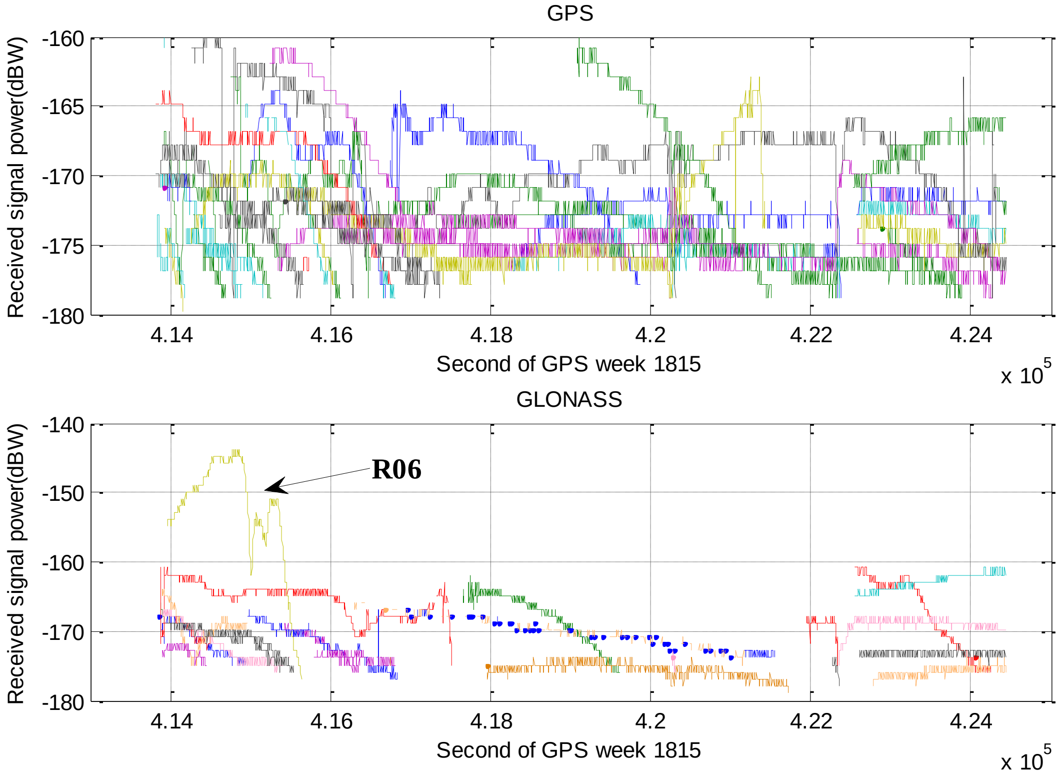


Figure 3. The received GNSS signal power

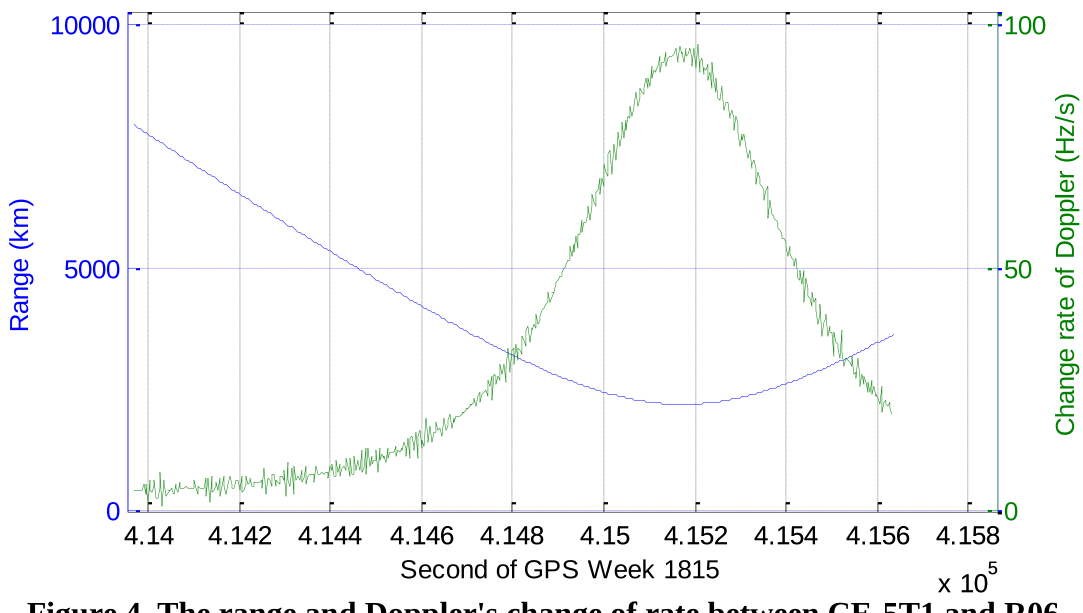


Figure 4. The range and Doppler's change of rate between CE-5T1 and R06

Further analysis can be done based on received signal power calculated above. There are now four blocks of GPS satellites in operation, which are IIA, IIF, IIR and IIR-M (http://www.glonass-iac.ru/en/GPS, updated in 2014.07.25). The Effective Isotropic Radiated

Power (EIRP) is a primary parameter to measure the performance of the satellite antenna and can be written as.:

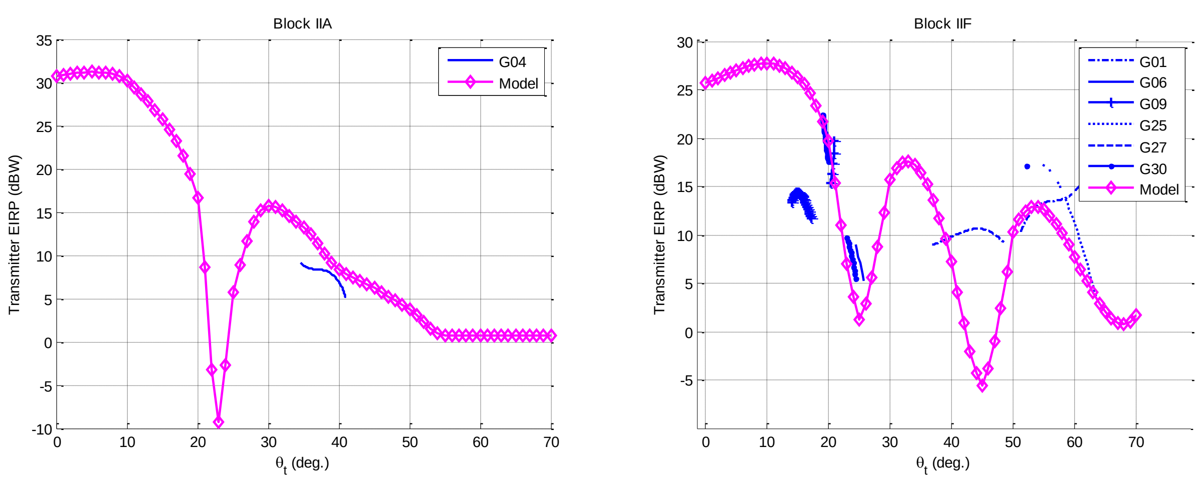
$$EIRP(\theta_t) = P_t + G_t(\theta_t) \qquad (2)$$

where θ_t is departure angle and G_t is the antenna gain; P_t is the transmit power and $P_t = 26.8dBW$ for GPS L1 signals. Czopek provides a set of measured gain data for a typical Block IIA GPS antenna array[10], which is the first reference regarding the GPS satellite antenna gain pattern. Based on Czopek's work, Moreau presents a modeled gain pattern for the antenna main beam, the first and the second side beam (0-70 degrees off boresight angle) in simulation[6]. Furthermore reference [8] provides the antenna gain pattern of Block IIR and IIF for beam width up to 65 degrees. Then the EIRP models of the three kinds of antenna based on the above references can be illustrated respectively, as shown in Figure 5; and the corresponding main beam width (3dB beam width) values are listed in Tab. 2.

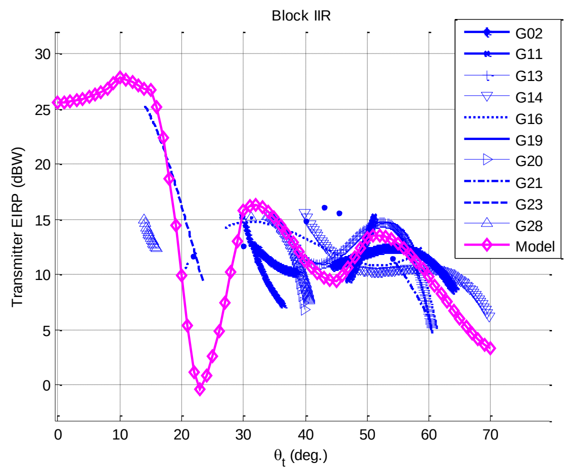
Meanwhile, the transmitter antenna EIRP can also be computed using the following equation:

$$EIRP(\theta_t) = P_s - L_p - G_r(\theta_r) \qquad (3)$$

where θ_r is the angle of incidence and G_r is the receiver antenna gain; the propagation loss L_P can be calculated using the well known equation $L_p = 20\log\left(\frac{\lambda}{4\pi d}\right)$ where λ is the wave-length of the GNSS signal and d is the propagation distance. The spacecraft-satellites relative position parameters demanded in Eq. 2 can be precisely estimated using the ephemeris data. Then the calculated EIRP values are plotted in Figure 5. Two important facts can be seen in these three charts: firstly, the majority of received signals are from side lobes, which is also validated by the statistical data in Tab.2; secondly, the three sets of real data do not fit the models perfectly well because of the noise and other error sources, but they coincide with each other in the trends and general level. Thus this results provide more credits to using these models in future simulations.



(a) (b)



(c)

Figure 5. The GPS satellite transmitter antennas EIRP derived from the received signal power

Table 2. The main beam width of GPS transmitter antennas and signal available time

Block	Main beam width	Main beam signal available time percentage	Side lobe signal available time percentage
IIA	17.87	0	1
IIF	16.92	18.735	81.265
IIR	16.17	2.402	97.598

3.2. GDOP

The computation of GDOP value needs at least 4 visible satellites. And the concept of satellite visibility here contains two ideas: on one hand, the light-of-sight is not obstructed by the Earth limb; on the other hand, the received signal power is sufficiently high for the receiver to do acquisition and tracking[7]. As introduced in section 2, the visible signal number for CE-5T1 spacecraft is not only constrained by the signal visibility itself but also by the receiver parallel processing ability. Fortunately, it can be seen in Figure 6(a) that 24 parallel channels are adequate in this situation. More than 8 GPS satellites are visible in most time while the number of visible GLONASS satellites rarely exceeds 6 and is less than 4 for about 7800 seconds in the middle of this period. Thus the GDOP value calculated using GPS+GLONASS satellites (black curve) and only GPS satellites (blue curve) are plotted in Figure 6(b). There is no big difference between the two curves because of GPS's superiority in satellite number. Either of the two curves bulges up to over 100 when the visible satellite number falls to 4. Except for the bump, the GDOP value is less than 20 when calculated using GPS+GLONASS satellites. According to reference [9], the average pseudorange measurement error of GPS signals for CE-5T1 SM receiver is about 4m (1σ) and that of GLONASS signals is about 8.7m (1σ). Then the corresponding positioning error if using both GPS and GLONASS signals is about 100m.

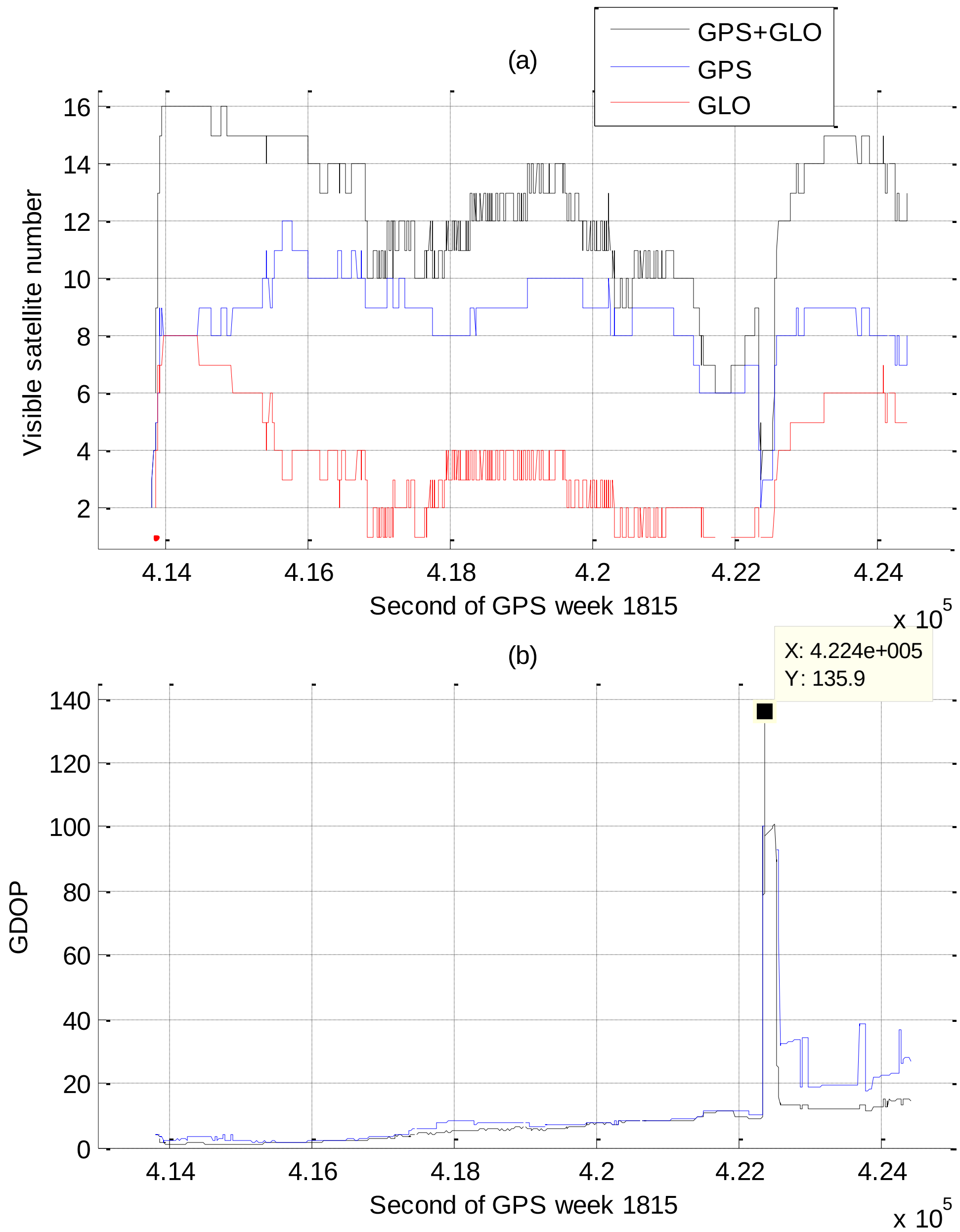


Figure 6. The visible satellite number and GDOP

As referred previously, CE-5T1 spacecraft was flying by satellite R06 during this period. This unique geometric position may contribute distinctively in the GDOP computation. we can measure this contribution using the following equation:

$$C_{GDOP}(x) = \frac{\sum_t GDOP_x(t)}{\sum_t GDOP_0(t)} \qquad (4)$$

where $GDOP_x(t)$ is the GDOP value calculated using all the visible satellites except satellite x (x= G01, ..., G32, R01, ..., R24) at the time represented by t, and $GDOP_0(t)$ is calculated with all visible satellites. All the GDOP values are summarized during the visible period of R06, which is the time span from 413967th to 415635th second of GPS Week 1815. C_{GDOP} of all satellites are plotted in Figure 7. It can be seen that the sum of GDOP values increases to almost 1.4 times if satellite R06 is excluded, while almost all other satellites' absence makes no difference to the GDOP value.

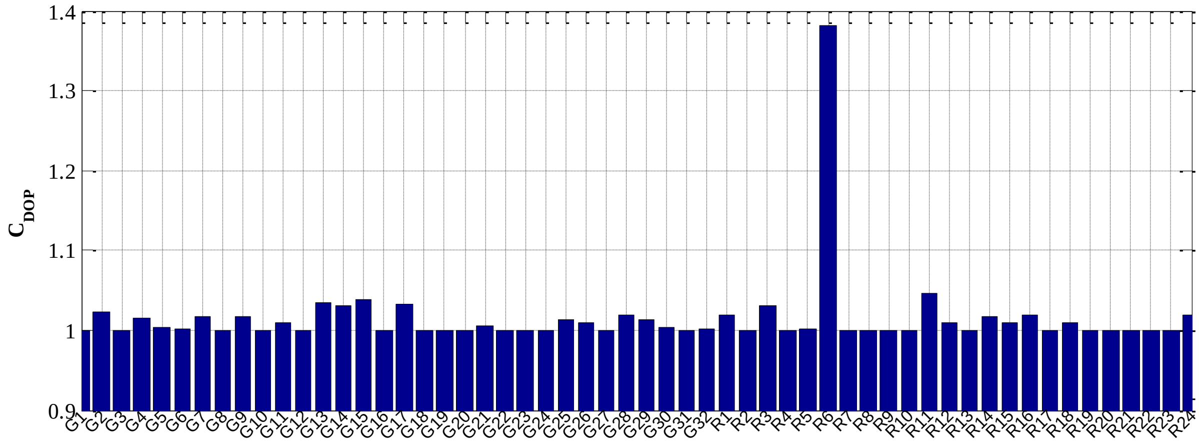


Figure 7. The contribution of each GNSS satellite to GDOP

4. Conclusions

GNSS-based satellite navigation is receiving increasing interest because of the economical and operational benefits. China's CE-5T1 spacecraft carried two GNSS equipments and collected a lot of precious data. The analysis in this paper illustrates the signal characteristics of GNSS signals received above the GNSS constellations and provides both theoretical and practical support for the use of GNSS in future Lunar missions.

5. References

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